Nonlinear Circuit Simulation and Modeling

Discover the nonlinear methods and tools needed to design real-world microwave circuits with this tutorial guide. Balancing theoretical background with practical tools and applications, it covers everything from the basic properties of nonlinear systems such as gain compression, intermodulation and harmonic distortion, to nonlinear circuit analysis and simulation algorithms, and state-of-the-art equivalent circuit and behavioral modeling techniques. Model formulations discussed in detail include time-domain transistor compact models and frequency-domain linear and nonlinear scattering models. Learn how to apply these tools to the design of real circuits with the help of a power amplifier design example, which covers all stages from active device model extraction and the selection of bias and terminations, through to performance verification. Realistic examples, illustrative insights, and clearly conveyed mathematical formalism make this an essential learning aid for both professionals working in microwave and RF engineering, and graduate students looking for a hands-on guide to microwave circuit design.

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"A much needed foundational and pedagogical treatment of how modern nonlinear approaches include and transcend their more familiar but overly restrictive linear precursors. Presented from multiple mathematical and conceptual perspectives, this book opens the door for both a richer theoretical understanding and a more confident application to real-world design challenges confronting today's engineers."

Jay Alexander, Chief Technology Officer, *Keysight Technologies*

"With the advent of more powerful computers, the importance of models in almost every sphere of engineering and science has continued to grow rapidly. The promise of being able to more easily and more accurately represent the non-linear effects of the real world and therefore design higher performing products more quickly is within our grasp. But it is rare to find a book which brings together the collection of knowledge to both understand and practice the new skills required to embrace and succeed with non-linear modeling - but this one does. The use of practical examples and the many visualizations of non-linear behaviour further help to cement fundamental conclusions. While the theory is presented, the book clearly demonstrates how this can be transferred into practical application with modern CAD tools. In an age where artificial intelligence and machine learning are all in vogue, linking models to physical processes helps engineers to pinpoint and address area for improvement in the real world."

Dr Mark Pierpoint, Senior Vice President, *Keysight Technologies*

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Fundamentals for Microwave Design

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"X-parameters" is a trademark of Keysight Technologies, Inc.

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Preface

The idea for this book had its genesis in the positive reception accorded to the short courses "Fundamentals of Device Modeling for Nonlinear Circuit Simulation and Microwave Design" and "The Basics of Computer Aided Nonlinear Microwave Circuit Design," which José Pedro and David Root presented for three years at two major international conferences. At that time, what moved us toward this endeavor was the shared view that there was a significant set of computer-aided design methods and techniques for nonlinear RF/microwave circuits that had not yet become standard practice for the vast majority of RF circuit designers. Despite the fact that most of the basic scientific results of nonlinear RF computer-aided engineering-based circuit design had already appeared in the late 1980s and had its boom of article publications in the 1990s and the beginning of the 2000s, the practicing engineer could not yet take full advantage of the enormous potential provided by this knowledge.

There are undoubtedly several reasons that can be advanced to explain the existing gap between the academic or industrial researcher and the practicing circuit designer. Among the most important reasons, we feel, is the engineering curriculum itself. In fact, even today, most bachelor- and master-level electrical engineering programs are still focused on linear analysis and design methods. So after graduation, when microwave engineers must face nonlinear circuits, they tend to base their designs on limited experience, heuristic extrapolations of familiar linear concepts beyond their domains of validity, and many trial-and-error iterations in the lab.

This book is intended to change this situation, filling the gap between the classical but restricted domain of linear microwave circuit design and the modern requirements for knowledgeable fundamentals of nonlinear circuit simulation and nonlinear device modeling. Being directed to both graduate students and RF design engineers, it adopts a hybrid approach in which basic mathematical foundations are presented along with many real examples. This way, this text goes all the way from the basics to the state-of-the-art in RF/microwave circuit simulation and device modeling. Since the mathematical formalism of nonlinear systems can be quite formidable, and even intimidating, it is always presented as a comparison to and an extension beyond the already known analysis of linear systems, and accompanied by simple illustrative application examples and exercises.

With this objective in mind, an introductory chapter starts the book, Chapter 1 – Linear and Nonlinear Circuits, in which the basics of nonlinear systems' responses to various types of stimuli are introduced as the natural result of lifting the linearity

restriction. Many important concepts, unknown in linear circuit design, such as gain compression, intermodulation, and harmonic distortion, are defined and then systematized using some simple and intuitive nonlinear mathematical models.

Then, Chapter 2 – Basic Nonlinear Microwave Circuit Analysis Techniques continues to the time-, frequency- and mixed-domain nonlinear circuit analysis and simulation algorithms, explaining the fundamental principles of the classic SPICE-like transient analysis and the workhorses of modern microwave circuit simulators: harmonic-balance and shooting (also known as the periodic-steady-state) methods. Finally, this chapter concludes with simulation techniques devoted to modern wireless signals such as envelope-following simulation engines and their enabled circuit-level/system-level co-simulation capabilities.

Because simulation requires numerical algorithms and device models, the next part of the book is devoted to the various equivalent-circuit and behavioral model formulations and extraction procedures. So, Chapter 3 – Linear Behavioral Models in the Frequency Domain: S-parameters starts with the linear behavioral model of microwave components, the S-parameter matrix, as an introduction to its extension to the nonlinear realm, to be treated in Chapter 4 – Nonlinear Frequency Domain Behavioral Models. Using a rigorous mathematical formalism, but also many practical measurements, the modern general framework of X-parameters is defined and carefully explained, with attention to pedagogy, from multiple perspectives, along with some simple, but insightful, examples.

Following this structure, Chapter 5 – Linear Device Modeling and Chapter 6 – Nonlinear Device Modeling address equivalent circuit models of microwave active devices with a particular emphasis on field-effect transistors. Discussing first the equivalent circuit concept and its limitations, the text then moves on to treat many different modeling approaches, such as arbitrary function approximation using ad hoc basis functions or systematic artificial neural-networks. However, such a theme would not be complete without many other practically important and scientifically challenging topics such as electro-thermal and trapping modeling, equivalent circuit model scaling, symmetry and charge and energy conservation principles.

Finally, to facilitate the comprehension of all these concepts and illustrate their application in a real engineering environment, the book concludes with Chapter 7 – Nonlinear Microwave CAD Tools in a Power Amplifier Design Example. This consists of the discussion of a practical nonlinear microwave circuit design, in which all design steps, from the active device model extraction, to the selection of bias and terminations, up to load- and source-pull prediction and the performance verification are addressed.

After collecting all material and then turning it into a coherent technical text, the authors hope that our readers will find it as exciting to read as it was for us to write. Actually, if our book causes more practicing engineers to use these computer-aided nonlinear microwave circuit design methods and techniques, then we will have fulfilled our initial goal.

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